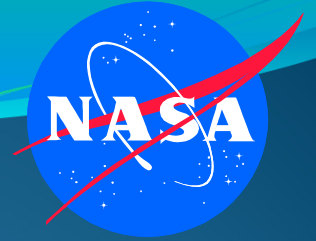


Investigation of High Current Events in Highly Scaled NAND Flash Memories

Farokh Irom and Duc N. Nguyen
Jet Propulsion Laboratory, California Institute of
Technology
Pasadena, CA 91109

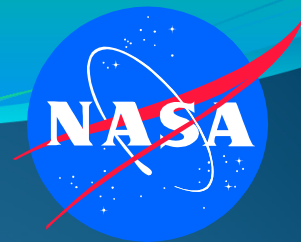
The research in this talk was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA), under the NASA Electronic Parts and Packaging Program.

Copyright 2011 California Institute of Technology Government Sponsorship Acknowledged.



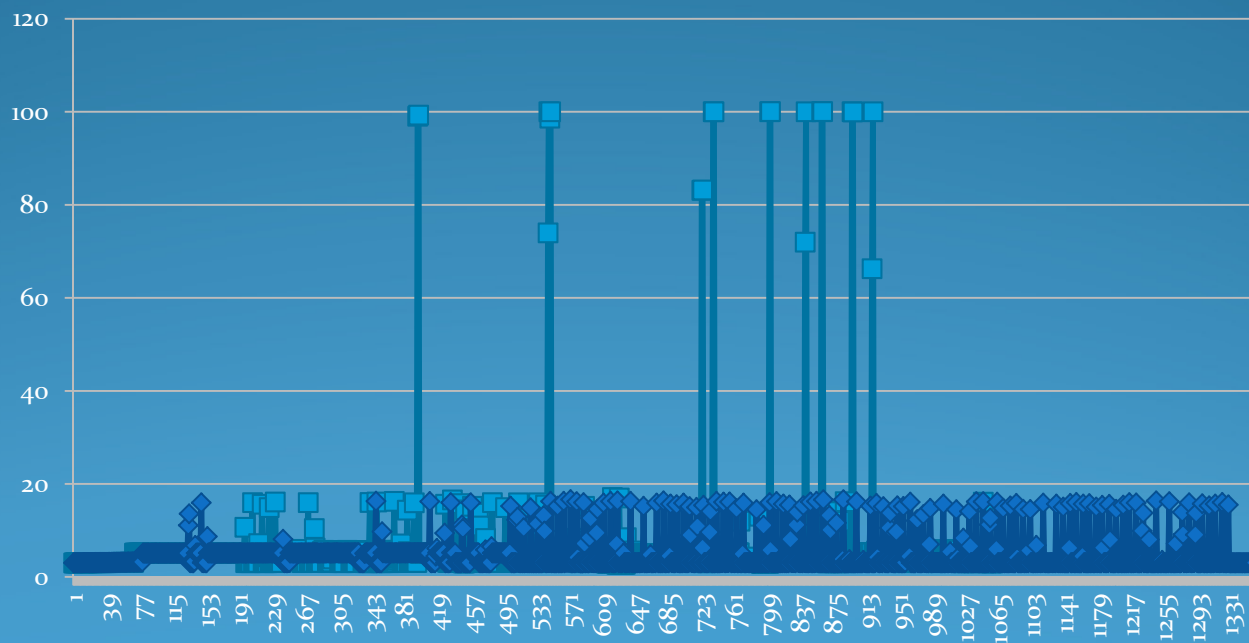
What JPL Reported

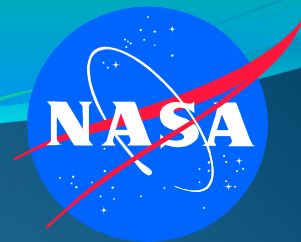
- Occurrence of relatively high current events during heavy ion testing of high density NAND flashes.
- The operating current for READ mode is about 3 mA, but the events can go as high as 300 mA .



What JPL Reported

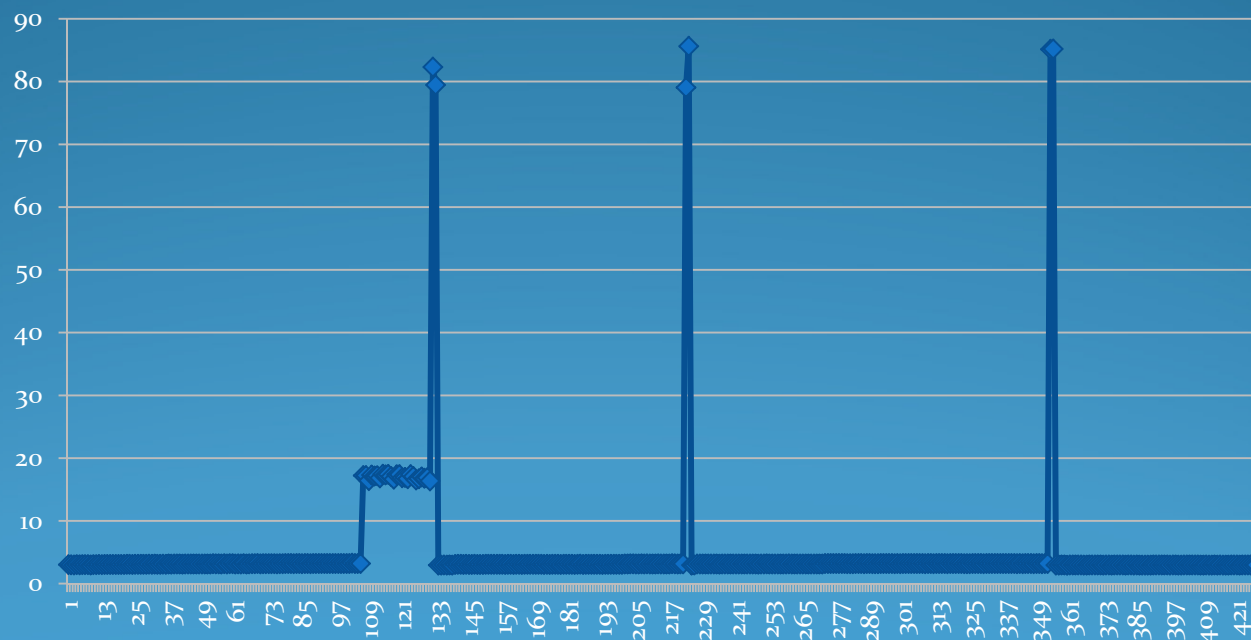
Micron 32Gb Ar LET=8.3 READ mode

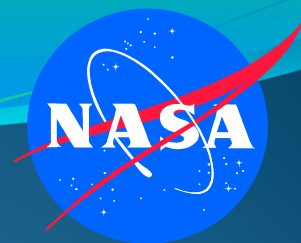




What JPL Reported

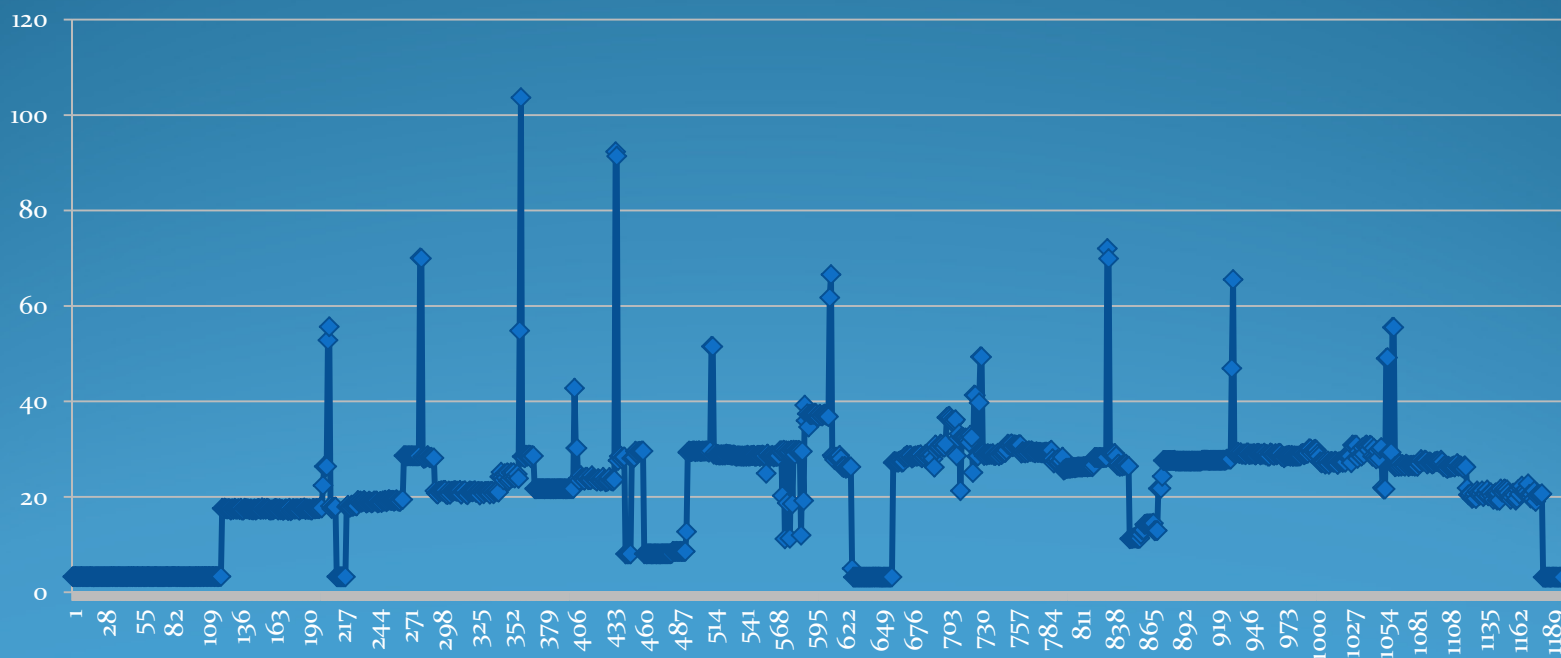
32Gb Micron Au LET=85 Program mode

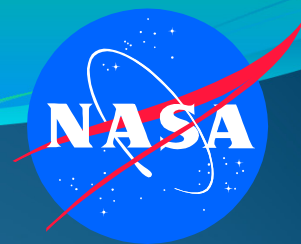




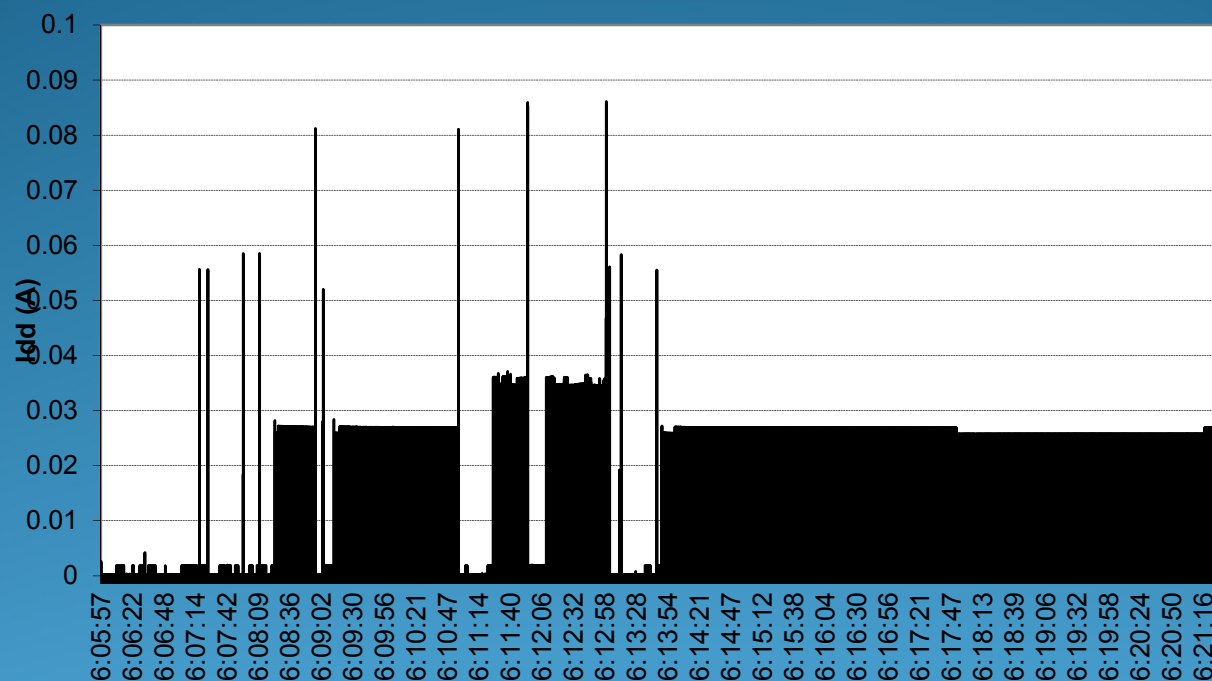
What JPL Reported

Samsung 8Gb Xe LET=51.5, PROGRAM mode TAMU





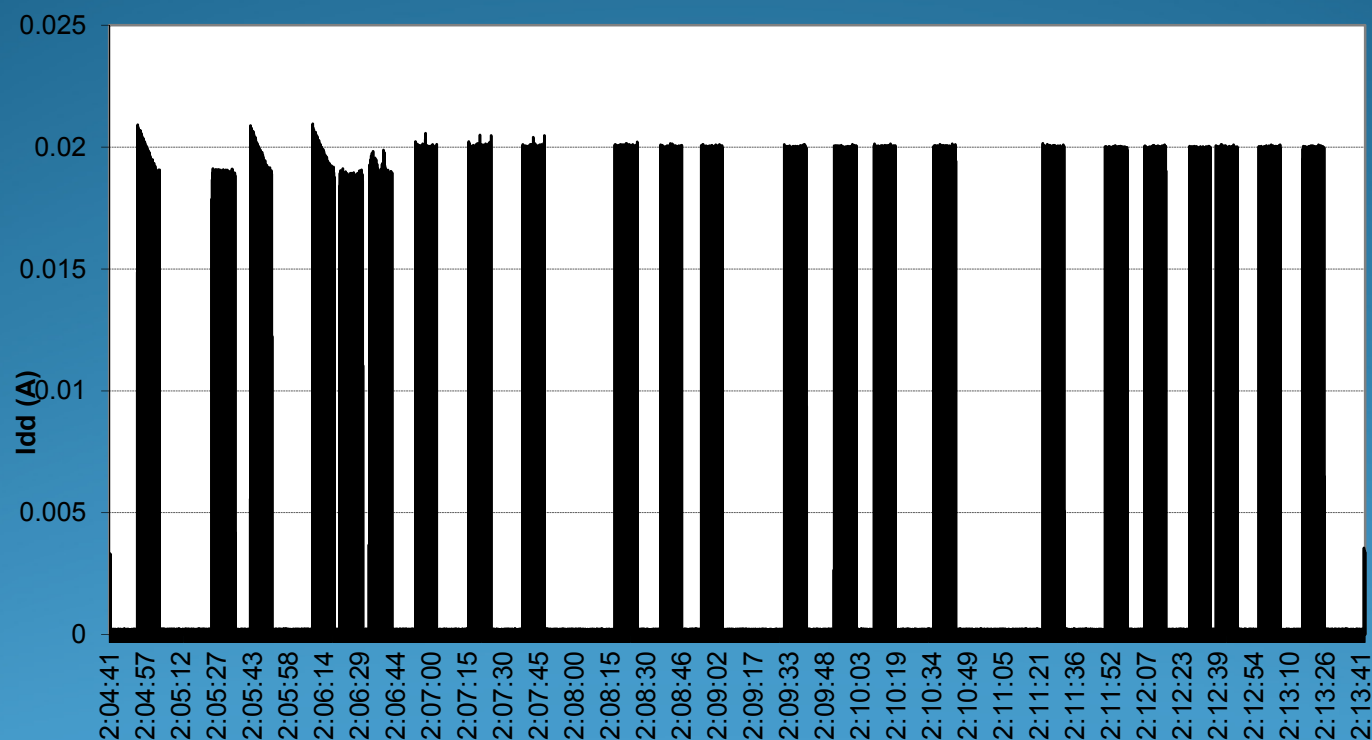
What JPL Reported



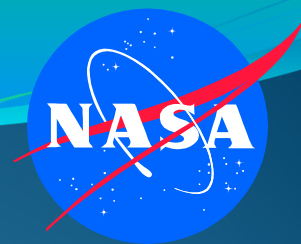
Current spectrum for Micron 2Gb READ mode. Data were taken with ^{181}Ta LET = 77.3 MeV-cm²/mg in READ mode at TAMU.



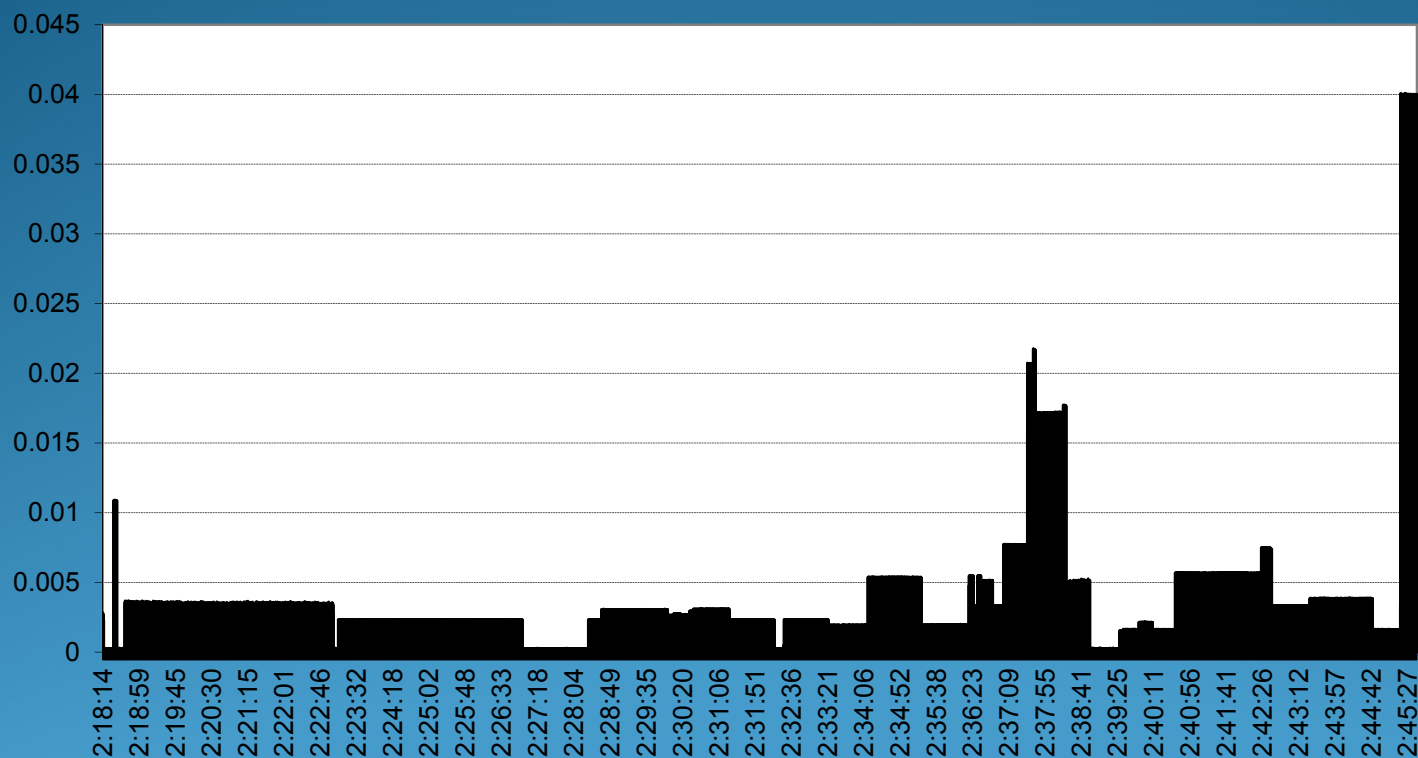
What JPL Reported



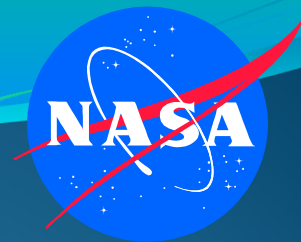
Current spectrum for Hynix 4Gb READ mode. Data were taken with ^{181}Ta LET = 77.3 MeV-cm²/mg in READ mode at TAMU.



What JPL Reported

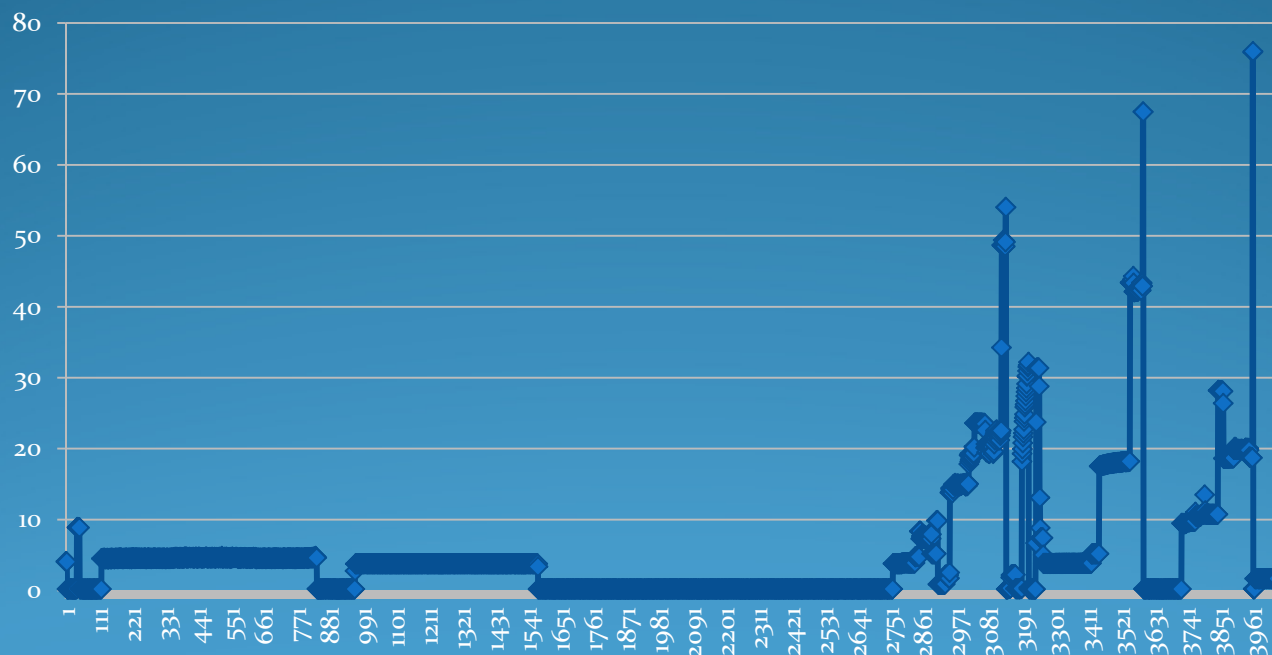


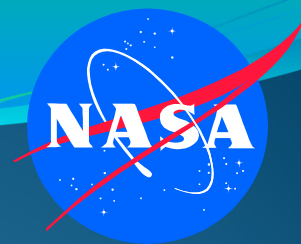
Current spectrum for ST Micro 2Gb READ mode. Data were taken with ^{181}Ta LET = 77.3 MeV-cm²/mg in READ mode at TAMU.



What JPL Reported

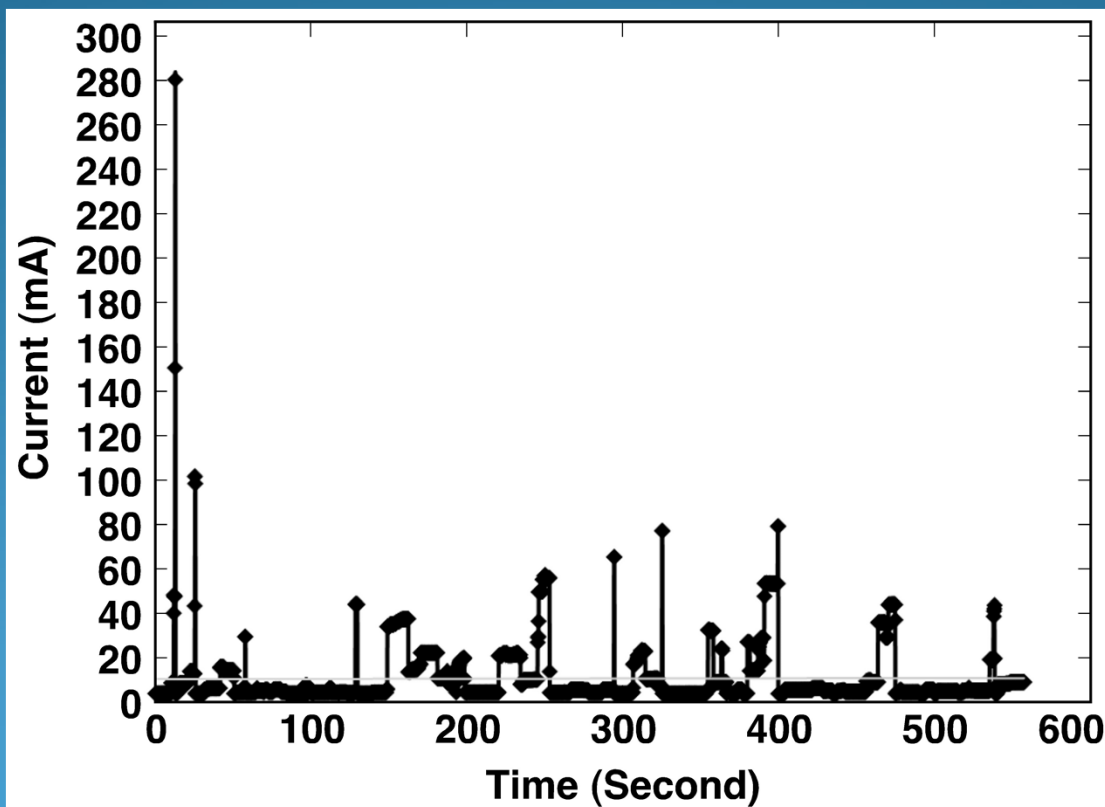
Samsung 1Gb ⁷⁹Br LET=37.3 BNL READ mode

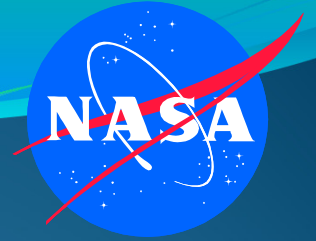




What JPL Reported

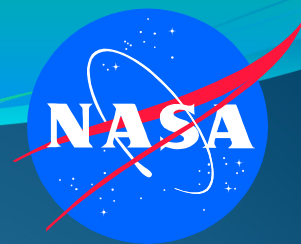
- The high current events were observed even in static mode under bias.





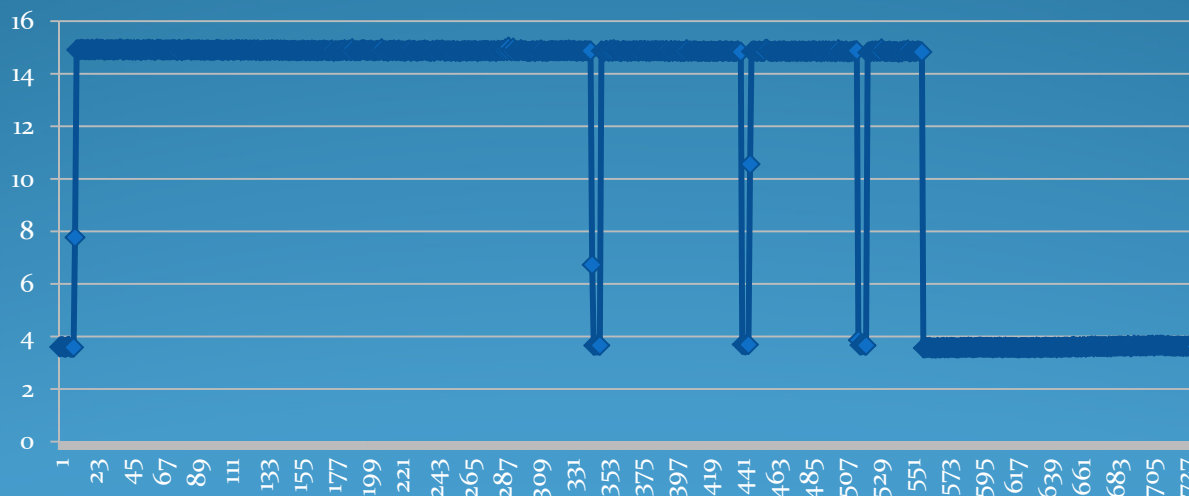
What JPL Reported

- The high current events should not be mistaken with a typical latchup event, because a latchup is defined to be a self-sustaining state. Although radiation causes the current to go up, it cannot stay in high current mode.
- The measurements show that it can last for couple of seconds or short period of about 600 ms.

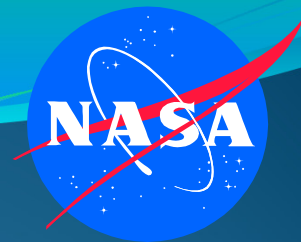


What JPL Reported

- The charge pump region and internal circuitry was masked. No high current events were observed.

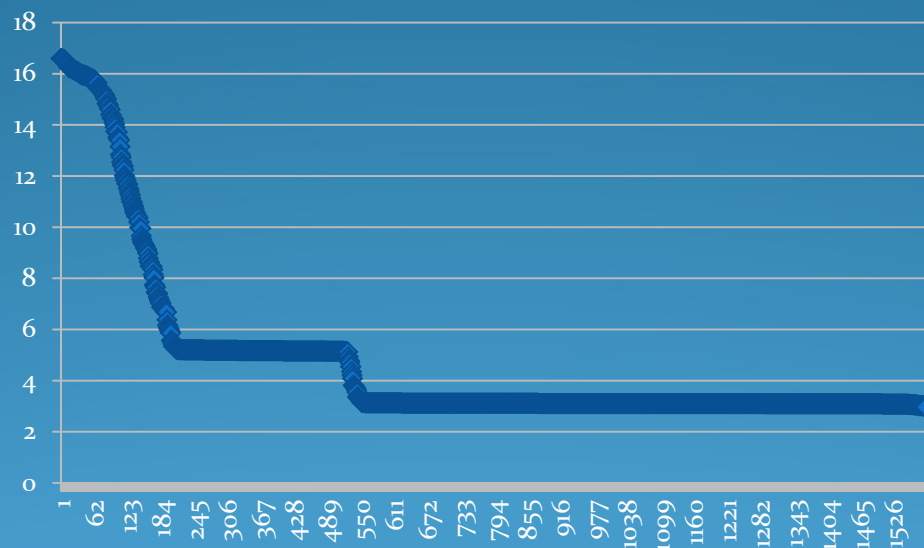


Samsung 8Gb Xe LET=51.5, READ mode CP Covered

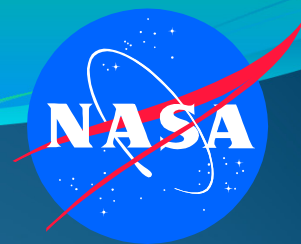


What JPL Reported

- The charge pump region and internal circuitry was masked. No high current events were observed.

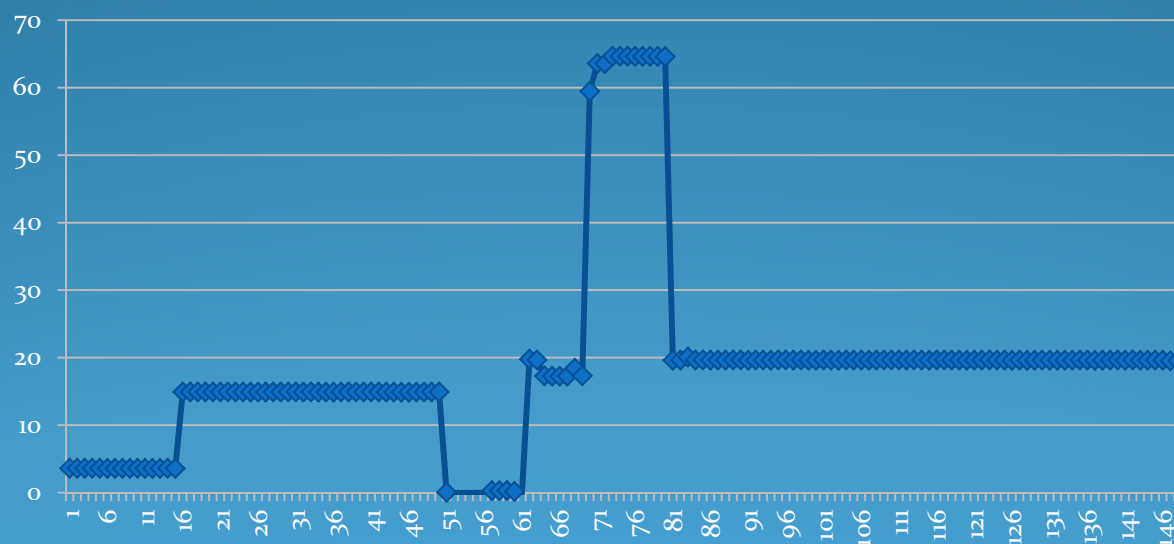


Micron 32Gb Au LET=85, READ mode CP Covered

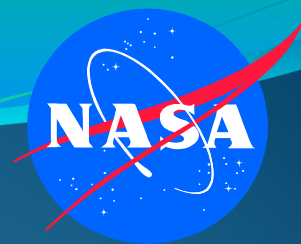


What JPL Reported

- In another shielding arrangement, the FG array was masked and the charge pump region exposed. High current events were observed.

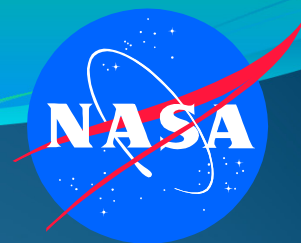


Samsung 8Gb Xe LET=51.5, READ mode FG Covered



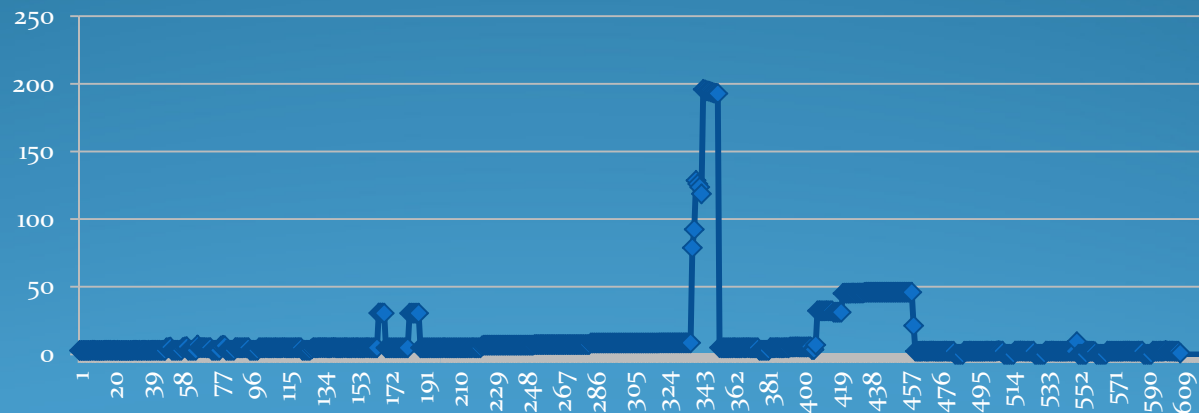
What JPL Reported

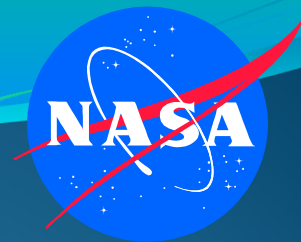
- The high currents event starts at low LETs (depending on feature size); however, high currents events lead to catastrophic failure at higher LETs.
- For Samsung 8Gb in READ mode, the high currents started at LETs below $27 \text{ MeV-cm}^2/\text{mg}$; however, high currents events lead to catastrophic failure at higher LET around $42 \text{ MeV-cm}^2/\text{mg}$.
- For 32Gb MLC Micron in PROGRAM mode, the high currents started at an LET around $8 \text{ MeV-cm}^2/\text{mg}$; however, high current events lead to a catastrophic failure at a higher LET around $19 \text{ MeV-cm}^2/\text{mg}$.
- Definition: We refer dead or catastrophically failed to a part which fails ERASE function. Catastrophic failure (the loss of ability to erase and program the device).



What JPL Reported

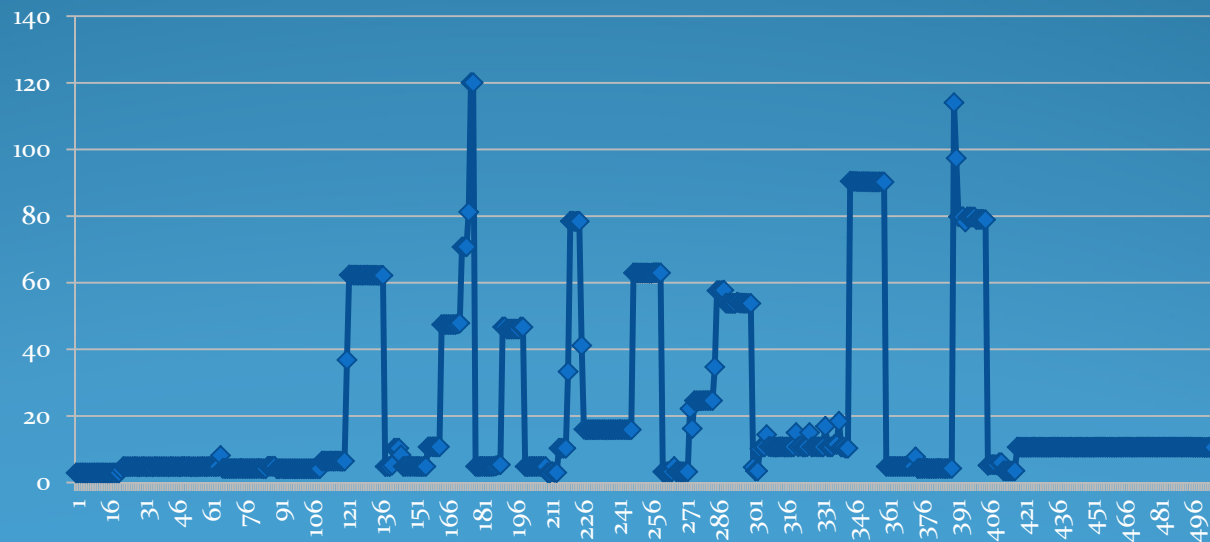
Samsung 8Gb LET=27.8, READ mode Non Destructive TAMU

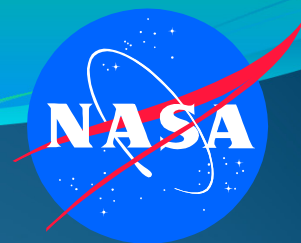




What JPL Reported

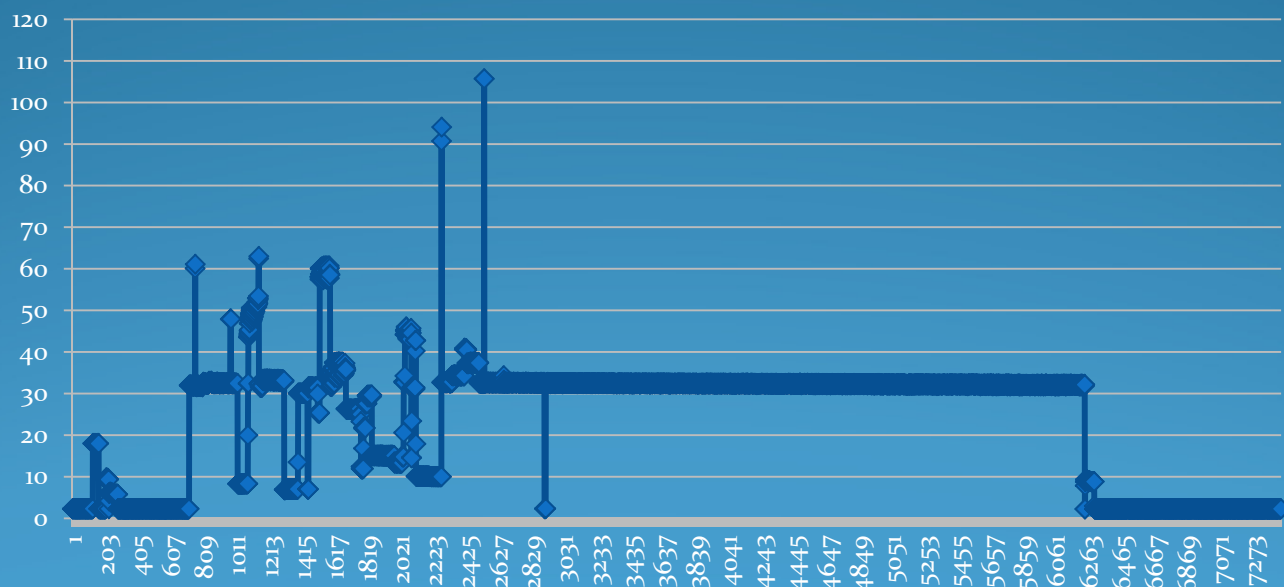
Samsung 8Gb Ag LET=42.2, READ mode Destructive TAMU

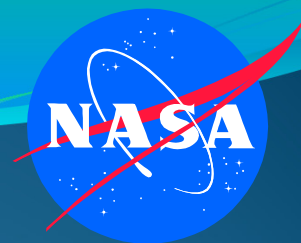




What JPL Reported

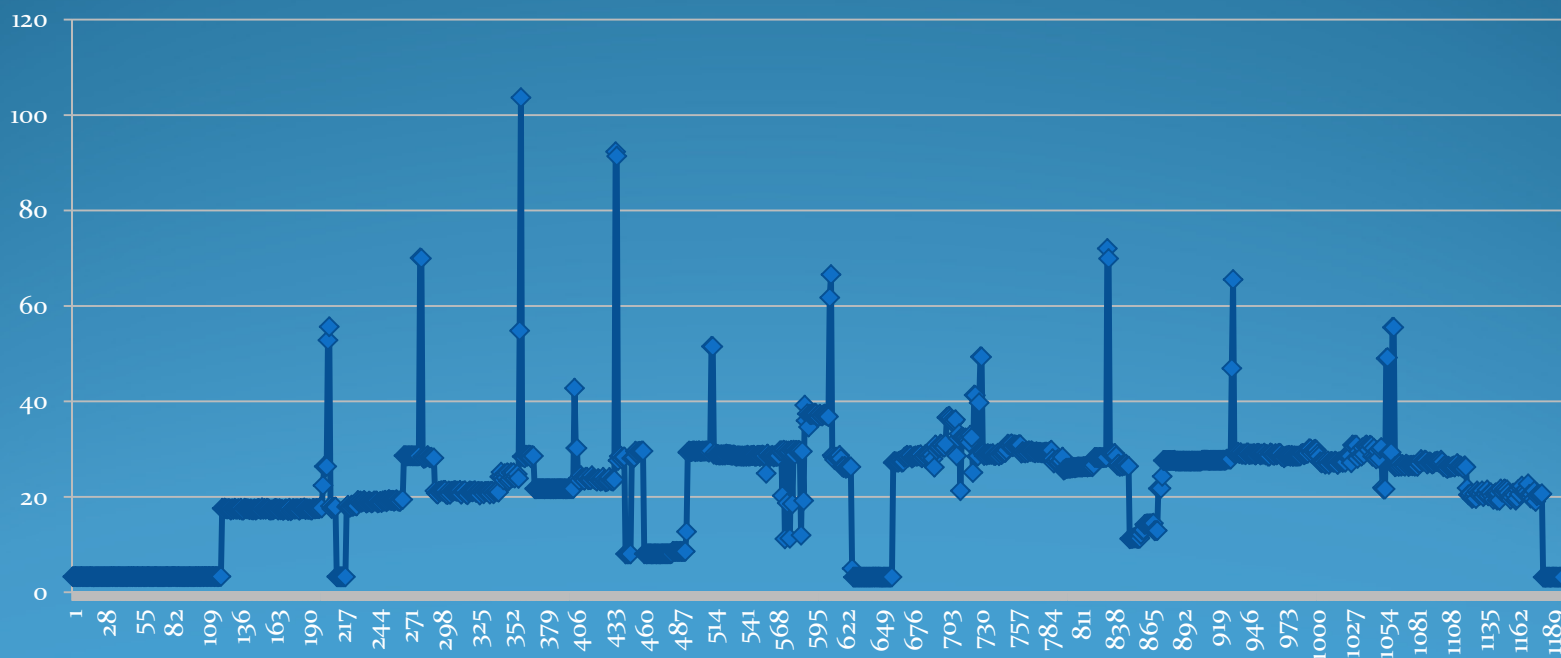
Samsung 8Gb LET=27.8, PROGRAM mode Non Destructive TAMU

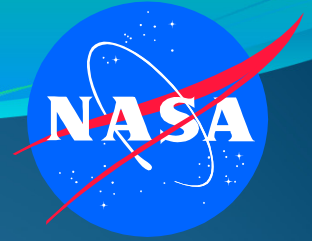




What JPL Reported

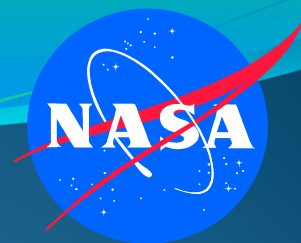
Samsung 8Gb Xe LET=51.5, PROGRAM mode Destructive TAMU



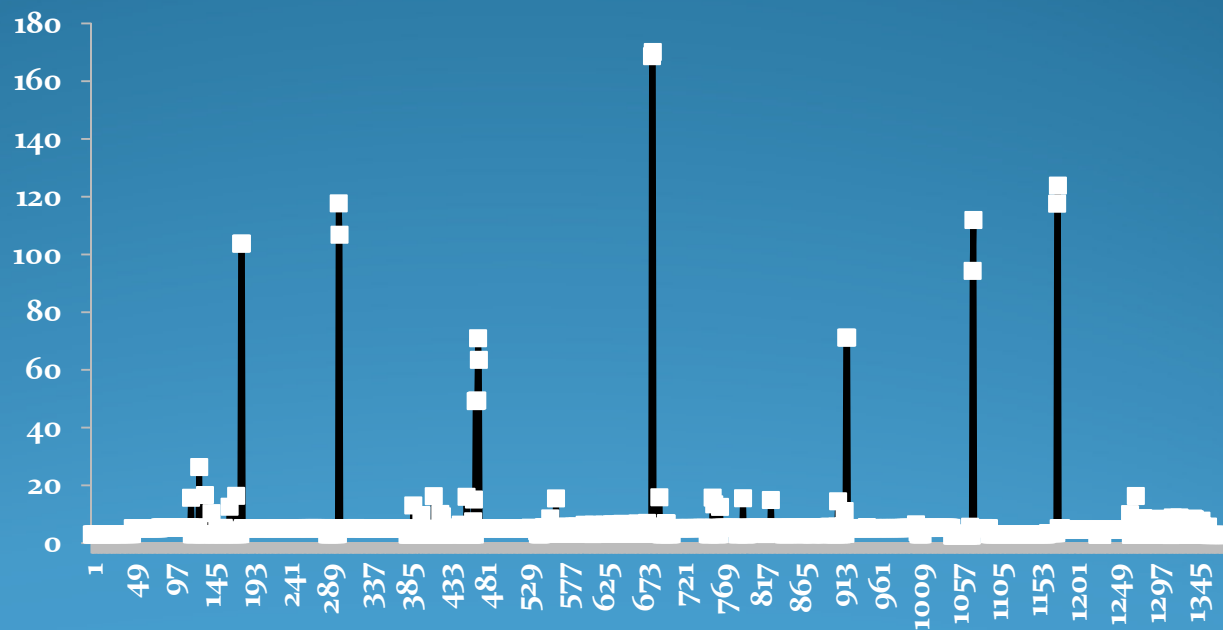


What JPL Reported

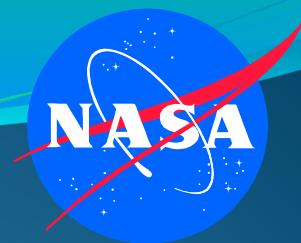
- The high current events are destructive for Samsung, Hynix, and ST Micro parts in dynamic READ, PROGRAM and ERASE modes and for Micron parts only in dynamic PROGRAM and ERASE modes.



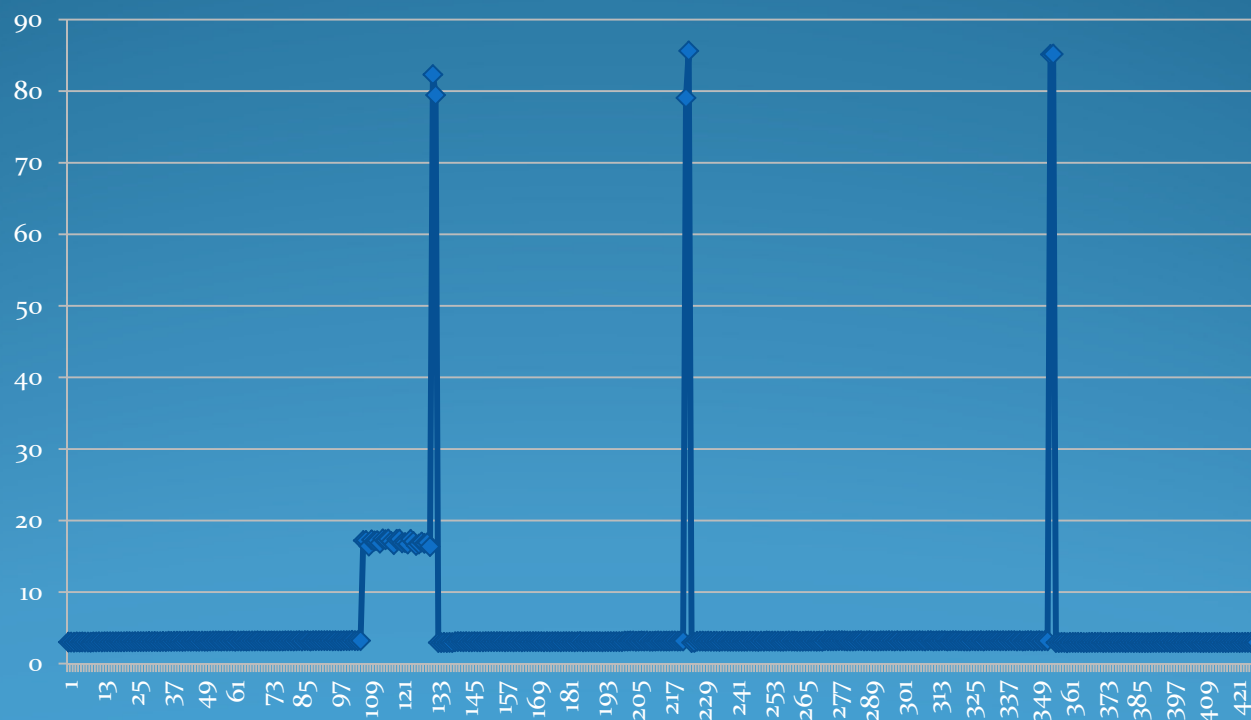
What JPL Reported



Micron 32Gb, AU LET=85.4, READ mode, TAMU Non Destructive



What JPL Reported



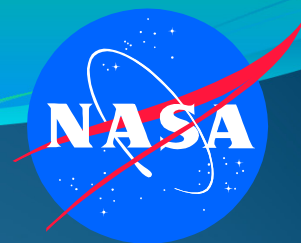
32Gb Micron Au LET=85 Program mode TAMU Destructive



What JPL Reported

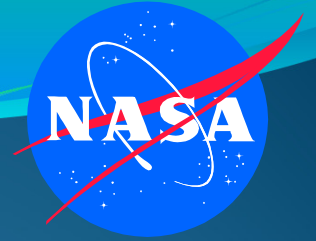
SUMMARY OF LET THRESHOLD FOR HIGH CURRENT EVENTS IN
READ MODE FOR PART THAT WE STUDIED.

Device	LET Threshold (MeV-cm ² /mg)	Mode
Micron 2Gb	55<LET _{th}	Non destructive
Micron 4Gb	55<LET _{th}	Non destructive
Micron 8Gb	27<LET _{th}	Non destructive
Micron 32Gb	8<LET _{th}	Non destructive
Hynix 4Gb	53<LET _{th}	Destructive
ST Micro 2Gb	37<LET _{th}	Destructive
Samsung 1Gb	37<LET _{th}	Destructive
Samsung 2Gb	37<LET _{th}	Destructive
Samsung 4Gb	37<LET _{th}	Destructive
Samsung 8Gb	27<LET _{th}	Destructive



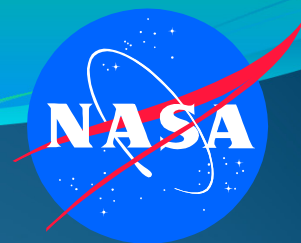
What JPL Reported

- The destructive high current events did not show any flux dependence.
- We did not observe any differences in the LET threshold for this catastrophic failure at RADEF, BNL and TAMU facilities.
- This phenomenon even occurred when the DUT was a virgin device and the dose delivered in that run was relatively low—approximately a couple of krads(Si)—confirming that the phenomena is not a consequence of accumulated TID, but due to single ions striking a sensitive area of the device. Subsequently, the effect was permanent and devices did not recover even after a high temperature anneal after being kept at 150°C for couple of hours.



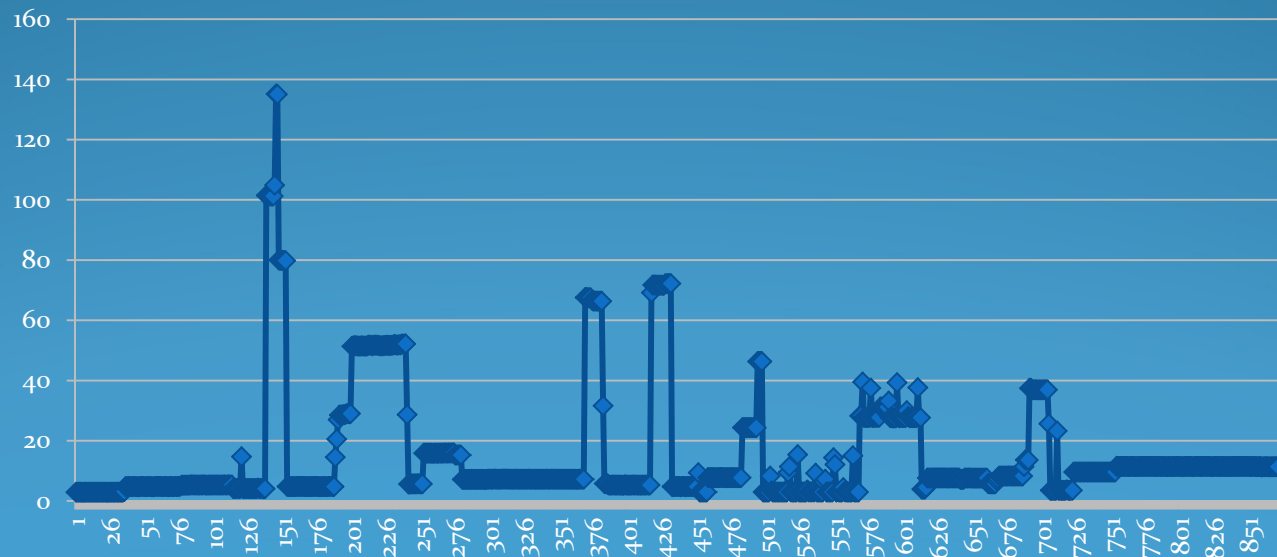
What JPL Reported

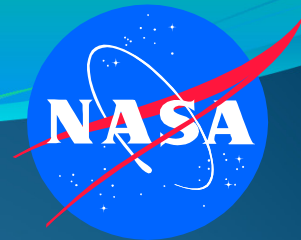
- We also performed some limited measurements to study the directional dependence of this phenomenon. Our limited results did not follow cosine law and suggest that device susceptibility might be nearly isotropic.



What JPL Reported

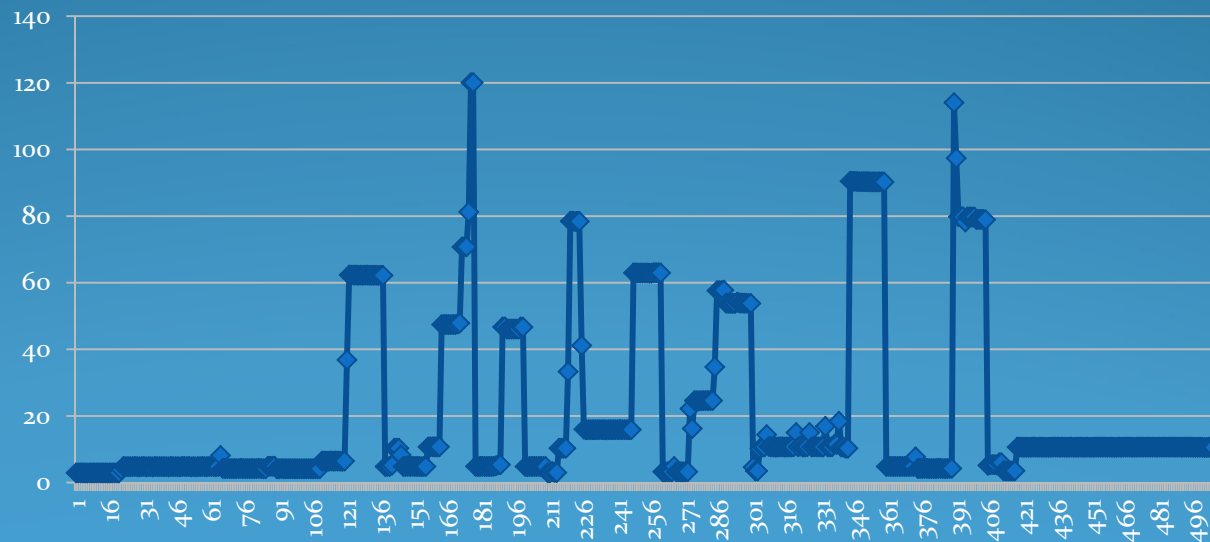
Samsung 8Gb Kr @ -45° LET_{eff} = 42.7, READ mode Non Destructive

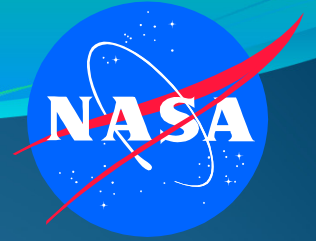




What JPL Reported

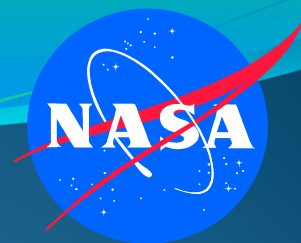
Samsung 8Gb Ag LET=42.2, READ mode Destructive TAMU





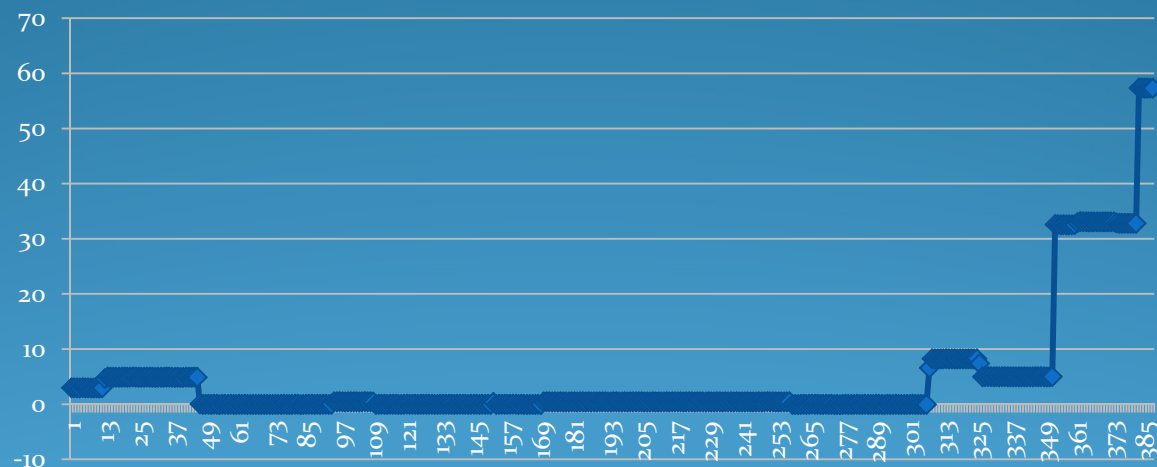
What JPL Reported

- The beam was stopped quickly as soon as the supply current exceeds 40mA. Catastrophic failure happened typically after first event (we tested only 6 parts in high LETs and in each test part died after first high current event).

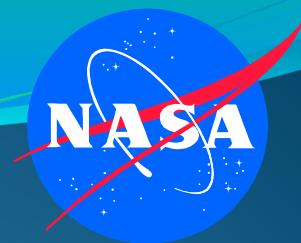


What JPL Reported

Samsung 8Gb Xe LET=51.5, READ mode Destructive TAMU

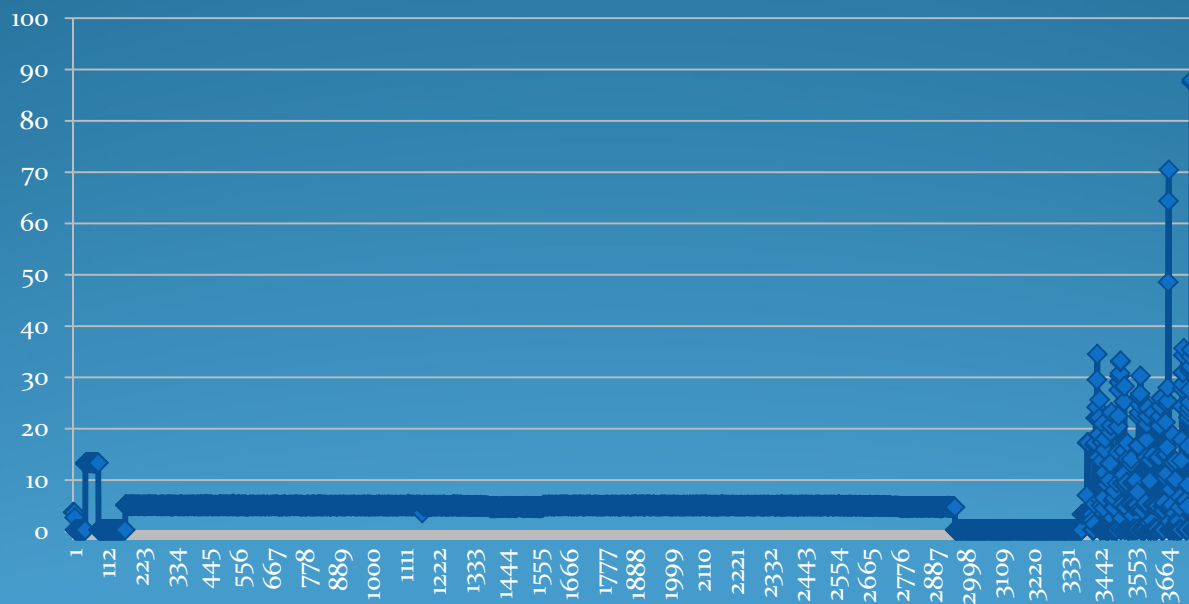


Beam was stopped after occurrence of first high current event.



What JPL Reported

Hynix 4Gb ^{107}Ag LET=53 BNL READ mode
Destructive

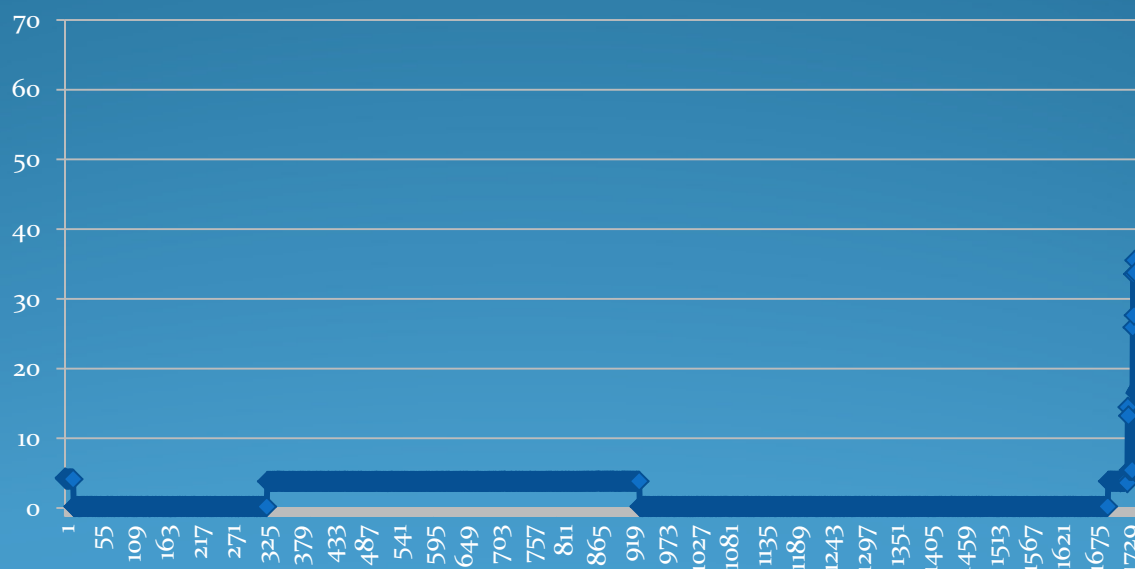


Beam was stopped after occurrence of first high current event.



What JPL Reported

Samsung 1Gb ^{127}I LET=60 BNL READ
mode Destructive

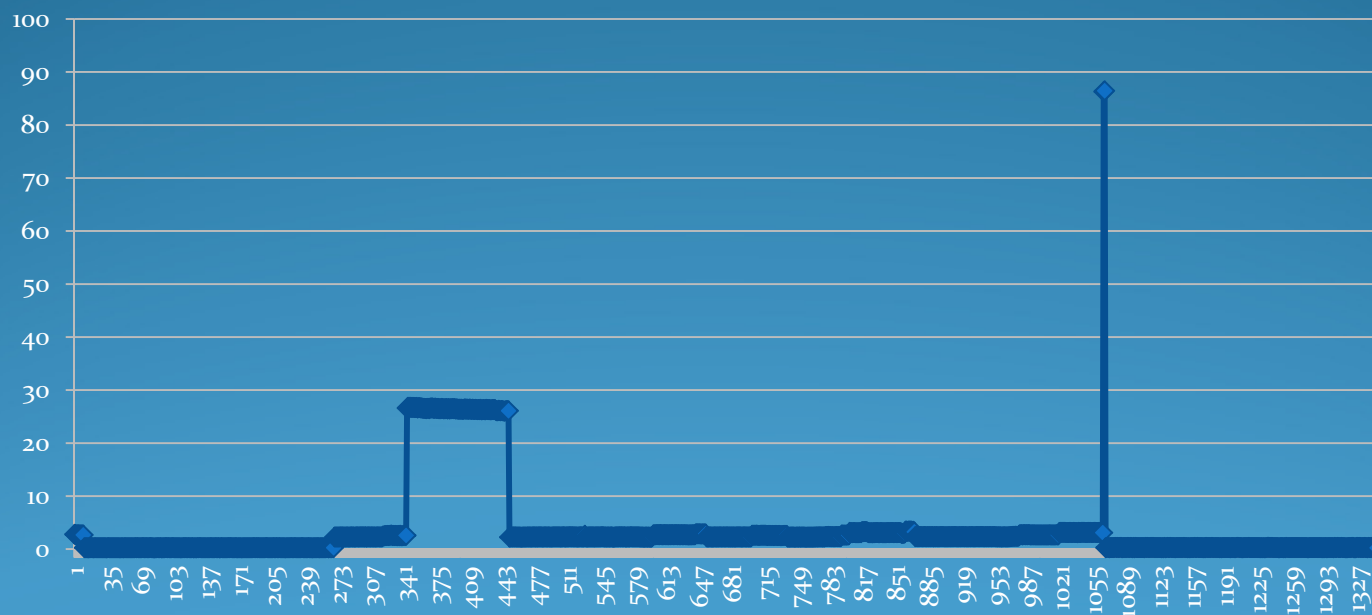


Beam was stopped after occurrence of first high current event.

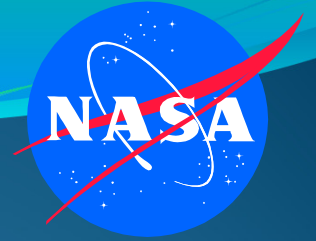


What JPL Reported

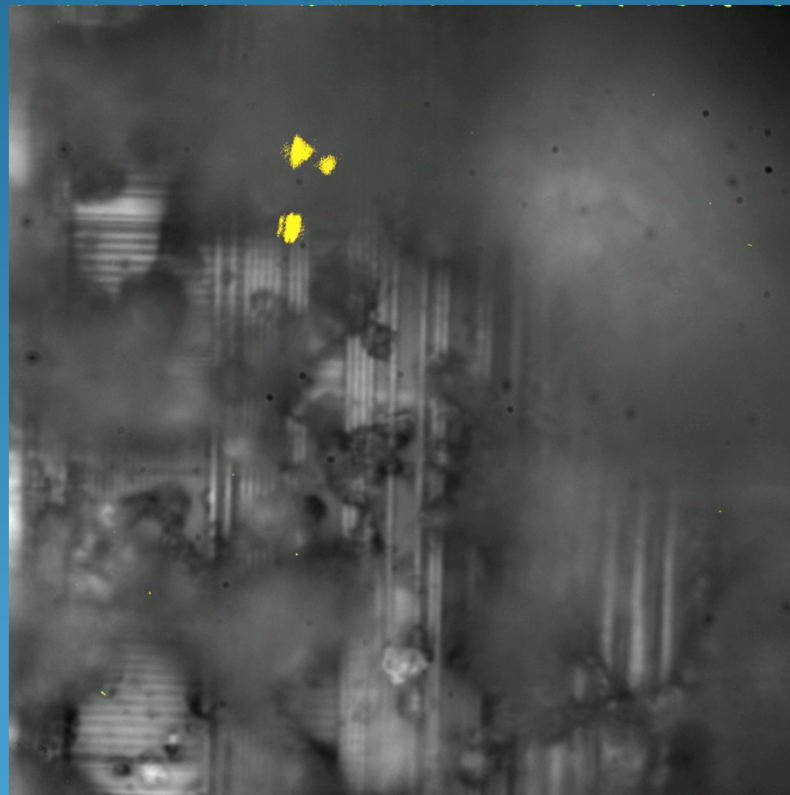
ST Micro 2Gb ^{107}Ag LET = 53 BNL READ mode
Destructive



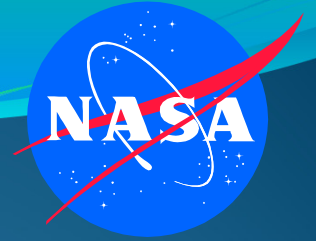
Beam was stopped after occurrence of first high current event.



What JPL Reported



Thermal picture of the charge pump region of the 8 Gb Samsung flash memory. The damaged area is clearly visible.

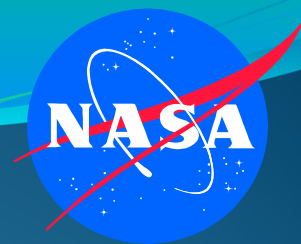


What JPL Reported

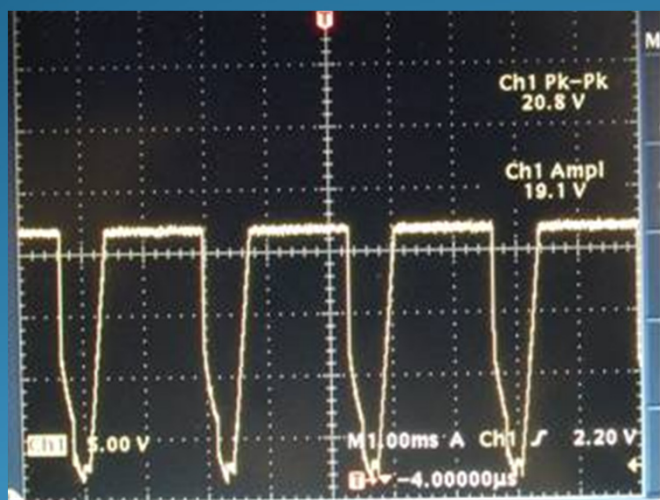
Samsung 1Gb



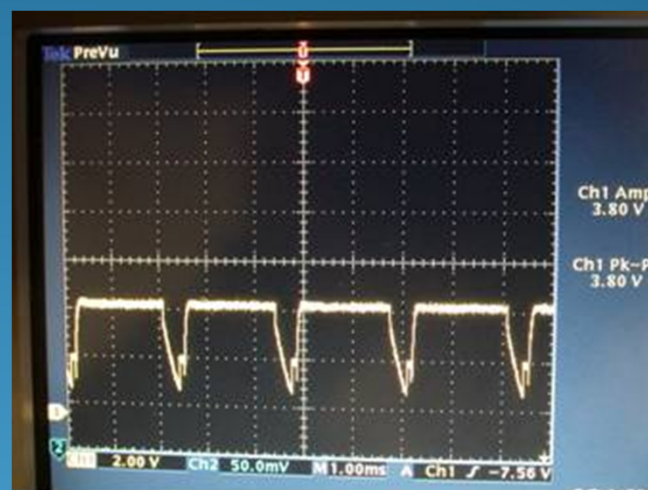
Tip of probe points to the monitor pad of Erase voltage.



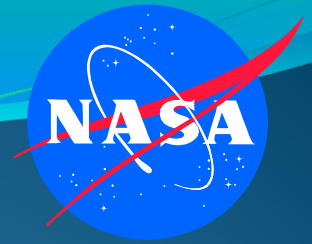
What JPL Reported



Initial pre-radiation erase voltage shows typical value of 20.8V.



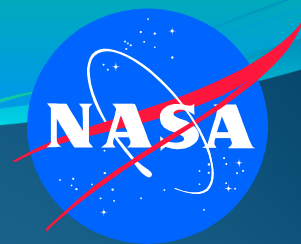
Charge pump degrades and erase voltage is down to 3.8V from 20.8V. Part can not be erased.



What JPL Reported

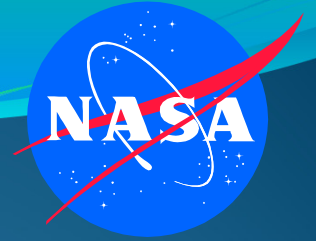
- The occurrence of high current events is not sensitive to temperature.

Measurements were also performed in READ mode in an extreme environment to test the destructiveness of the high current events for Micron NAND flash memories. The test was performed at elevated temperature of 80°C and the supply voltage was increased to 3.6 V in READ mode. After irradiating the Micron 4Gb part at LET 77.3 MeV-cm²/mg, with 5×10^7 ¹⁸¹Ta ions per cm², although the device was functional, half of the blocks (2048) were not writable or erasable. The bad blocks recovered gradually after annealing at room temperature. All blocks were writable or erasable after 48 hours.



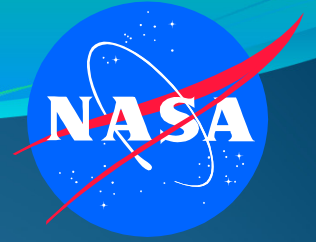
Conclusion

- Originates from the charge pump region/ internal circuitry
- Very low probability event ($2E-7$ per day per device)
- Can be destructive at high LETs
- No flux dependence was observed
- No Angular dependence (did not follow cosine law)
- No temperature dependence
- No SEL or Bus Contention



What JPL Reported

- We did not observe any differences in the LET threshold for this catastrophic failure at both BNL and TAM facilities.



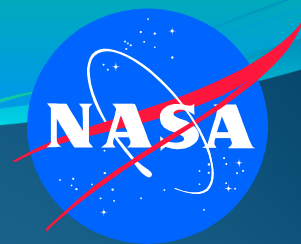
BACKUP



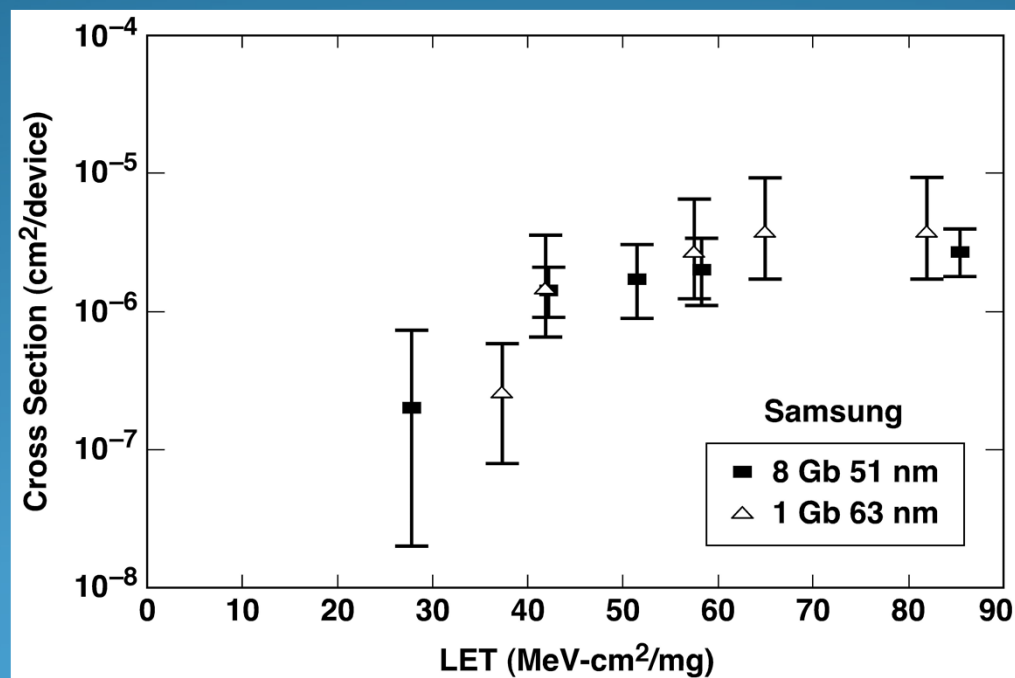
What JPL Reported

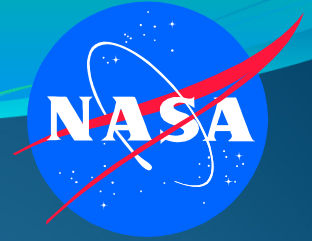
SUMMARY OF LET THRESHOLD FOR HIGH CURRENT EVENTS IN
READ MODE FOR PART THAT WE STUDIED.

Device	LET Threshold (MeV-cm ² /mg)	Mode
Micron 2Gb	55<LET _{th}	Non destructive
Micron 4Gb	55<LET _{th}	Non destructive
Micron 8Gb	27<LET _{th}	Non destructive
Micron 32Gb	8<LET _{th}	Non destructive
Hynix 4Gb	53<LET _{th}	Destructive
ST Micro 2Gb	37<LET _{th}	Destructive
Samsung 1Gb	37<LET _{th}	Destructive
Samsung 2Gb	37<LET _{th}	Destructive
Samsung 4Gb	37<LET _{th}	Destructive
Samsung 8Gb	27<LET _{th}	Destructive



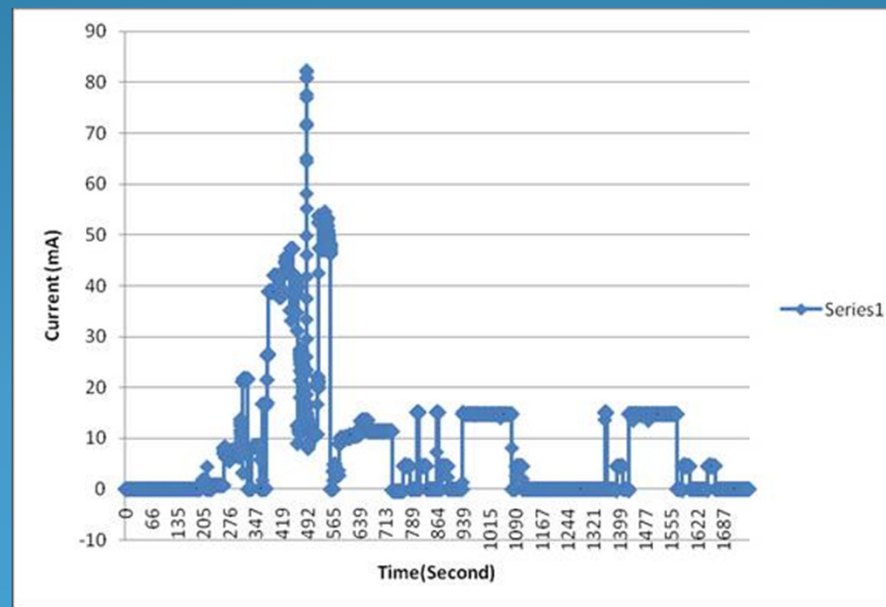
What JPL Reported



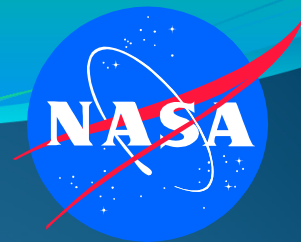


Results of JPL/GSFC Joint Test

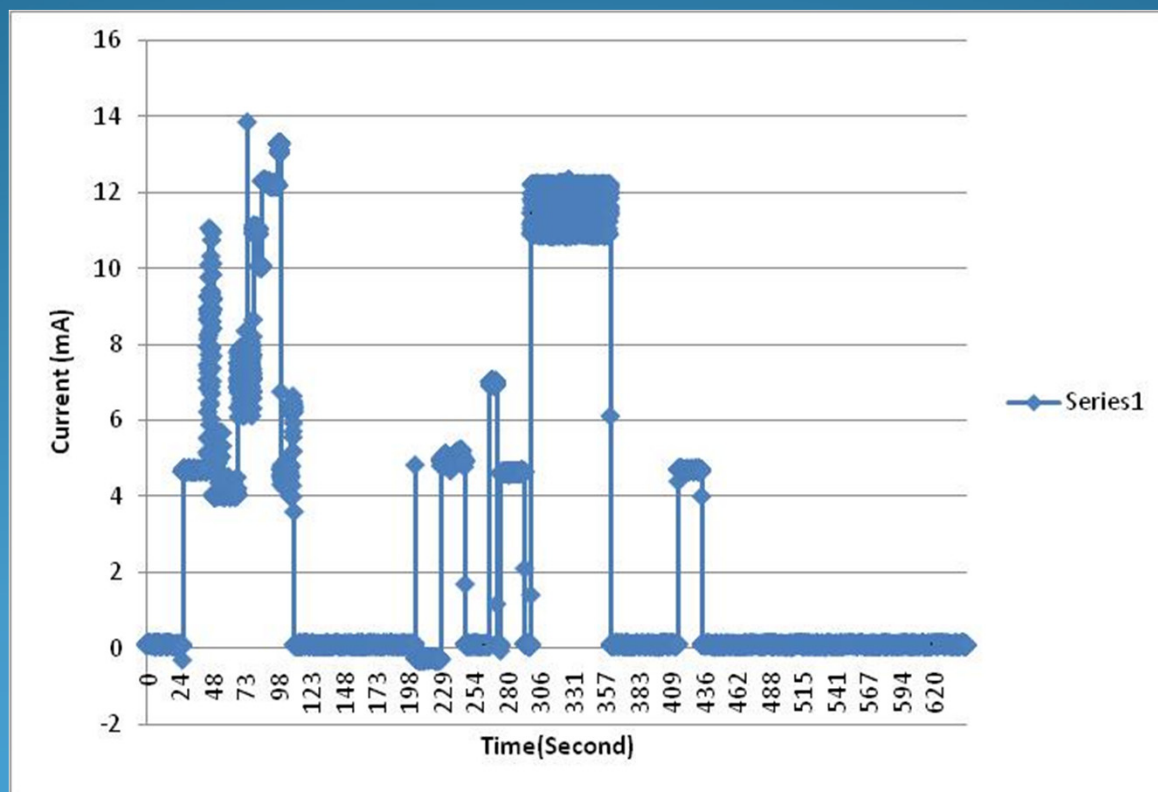
- High current events were observed



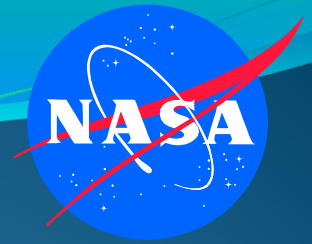
Micron 4Gb Static Mode



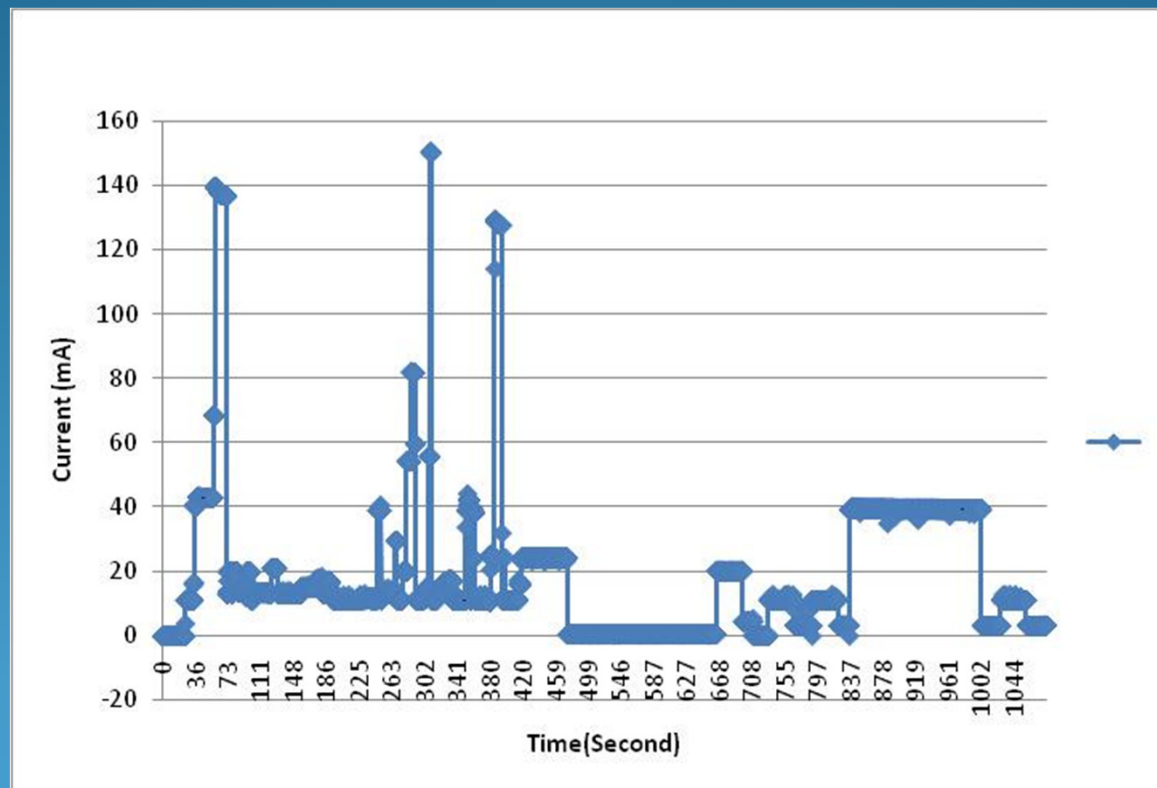
Results of JPL/GSFC Joint Test



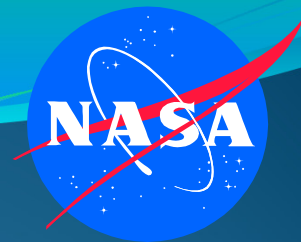
Micron 4Gb READ/PROGRAM/ERASE mode



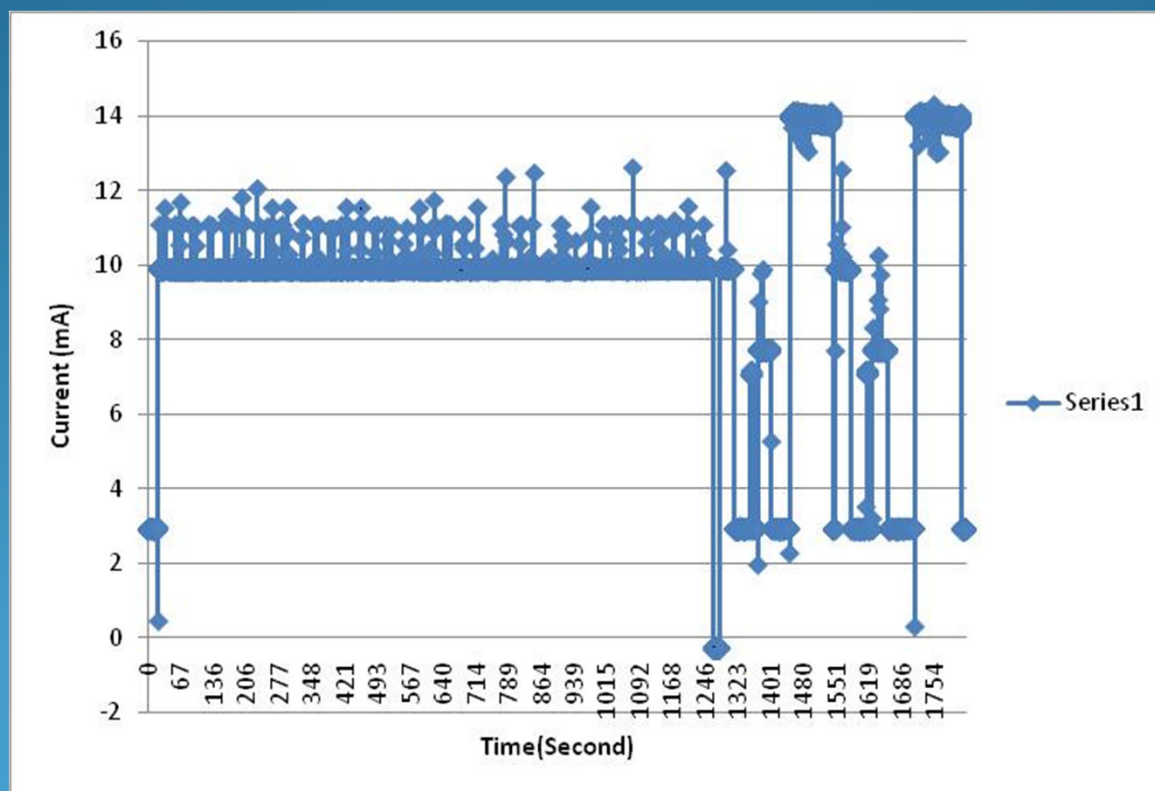
Results of JPL/GSFC Joint Test



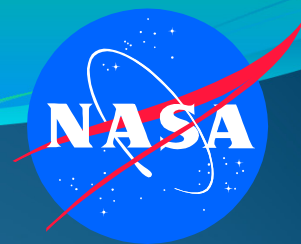
Samsung 8Gb READ mode



Results of JPL/GSFC Joint Test

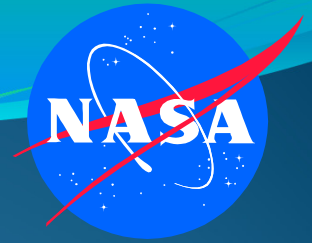


Samsung 8Gb READ mode



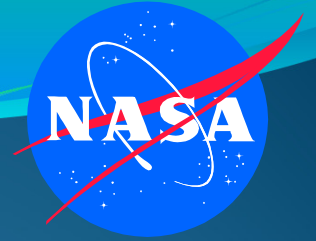
Results of JPL/GSFC Joint Test

- No flux dependence was observed
- The charge pump region and internal circuitry was masked. No high current events were observed
- The high current events were observed even in static mode under bias
- The high current events were destructive for Samsung parts in Static, Dynamic READ, and Dynamic READ/PROGRAM/ERASE modes
- The high current events were destructive for Micron parts only in Dynamic READ/PROGRAM/ERASE mode



Comparison

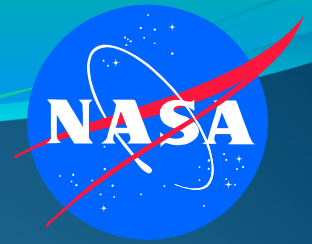
	JPL	JPL/GSFC
High current observed	Yes	Yes
Flux Dependence	No	No
Originated from charge pump region	Yes	Yes
Destructive for Samsung in static mode	Yes	Yes
Destructive for Samsung in dynamic R mode	Yes	Yes
Destructive for Samsung in dynamic R/E/P	Yes	Yes
Destructive for Micron in static mode	Not tested	Yes
Destructive for Micron in Dynamic R	No	No
Destructive for Micron in dynamic R/E/P	Yes	Yes



What GSFC Reported

T. R. Oldham et al., "Effects of Heavy Ion Exposure on Nano Crystal Nonvolatile Memory," TNS, VOL. 52, NO. 6, DECEMBER 2005

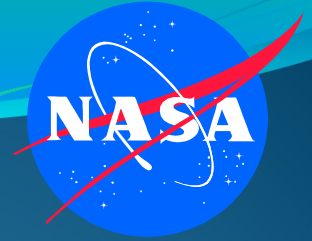
"The circuit went into a high current state after most exposures at all LETs tested. The circuit was fully functional, even in the high current state, which suggests that it was not the result of a general latchup. After the latchup, the floating gate circuits could not be erased or written, but they could still be read. In addition, there was a possible gate rupture in a read test with Au ions incident."



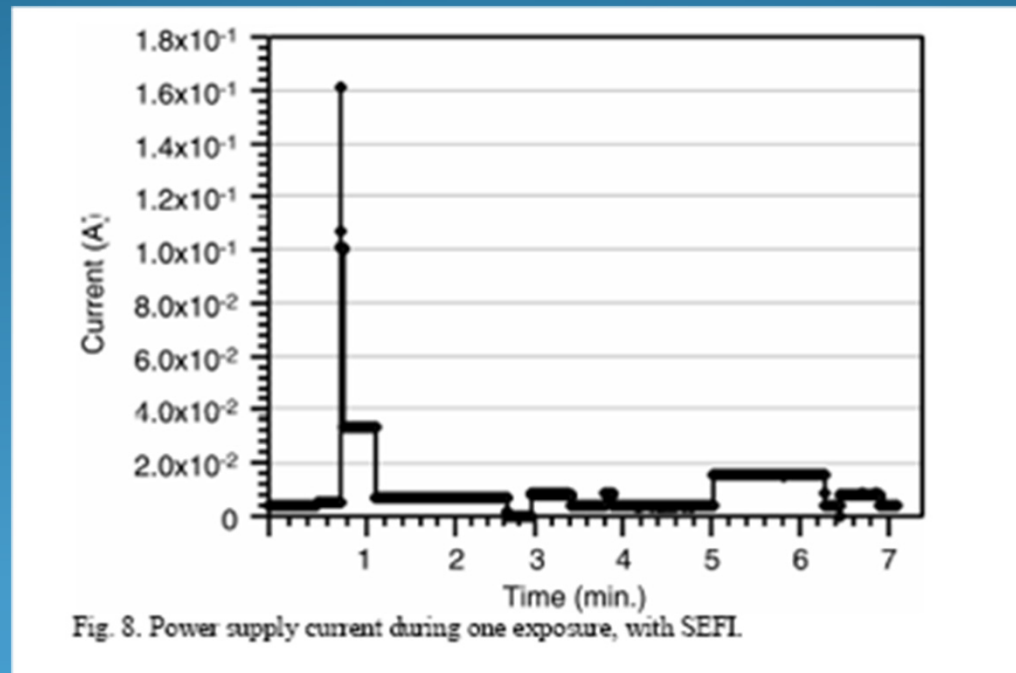
What GSFC Reported

T. R. Oldham et al., "SEE and TID Characterization of an Advanced Commercial 2Gbit NAND Flash Nonvolatile Memory," TNS, VOL. 53, NO. 6, DECEMBER 2006

"Results are qualitatively similar to previous flash results in most respects, but we also detected a new dynamic failure mode. Functional failures (destructive events) were observed that made it impossible to Erase or Write to the memory. These events are probably due to Single Event Gate Rupture (SEGR). SEGR was first identified by Blandford et al., in nonvolatile memories during high-voltage write and erase operations."



What GSFC Reported



T. R. Oldham et al., "TID and SEE response of an advanced Samsung 4Gb NAND flash memory," NSREC data workshop, 2007